

# Waxing and Waning of Observed Extreme Annual Tropical Rainfall

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We begin by providing observational evidence that the probability of encountering very high and very low annual tropical rainfall has increased significantly in the recent decade (1998-present) as compared to the preceding warming era (1979-1997). These changes over land and ocean are spatially coherent and comprise of a rearrangement of very wet regions and a systematic expansion of dry zones. While the increased likelihood of extremes is consistent with a higher average temperature during the pause (as compared to 1979-1997), it is important to note that the periods considered are also characterized by a transition from a relatively warm to cold phase of the El Niño Southern Oscillation (ENSO). To further probe the relation between contrasting phases of ENSO and extremes in accumulation, a similar comparison is performed between 1960-1978 (another extended cold phase of ENSO) and the aforementioned warming era. Though limited by land-only observations, in this cold-to-warm transition, remarkably, a near-exact reversal of extremes is noted both statistically and geographically. This is despite the average temperature being higher in 1979-1997 as compared to 1960-1978. Taken together, we propose that there is a fundamental mode of natural variability, involving the waxing and waning of extremes in accumulation of global tropical rainfall with different phases of ENSO.

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## I. INTRODUCTION

In the context of global warming, the increasing moisture content of the troposphere [23, 48] is expected to result in an amplification of short-duration extreme rainfall events [5, 37, 47], mostly validated by regional ground-based observations [13, 18, 21]. On longer timescales, a consequence of the increase in column integrated water vapour for locations with very high and low accumulation is the so-called thermodynamic effect of “wet regions getting wetter, and dry regions getting drier” [23, 53]. Some observations [4, 7, 27] and long-term global warming simulations [8, 17, 26, 36] are consistent with the expected consequences of this paradigm. In addition, dynamical changes due to warming also affect rainfall [46]. The combination of these two complicate the precipitation response [6, 55], especially over land [19]. In fact, as suggested by [28, 29], the “wet-wetter, dry-drier” hypothesis may be more appropriate over land if the wet and dry regions are not considered to be fixed geographical locations [see also, 41].

Apart from the role of warming, it has been suggested that changes in regional extremes have a natural component. In particular, individual locations with more than a century long data clearly exhibit multiple cycles in heavy rainfall [see for example, 32, 54]. Further, it has been documented that regional extremes in rainfall vary with El Niño and La Niña conditions [see 15, 20, 25, 51, for reports on the continental United States, South America, eastern Australia and the Philippines, respectively]. In fact, connections between daily and monthly extremes and the El Niño Southern Oscillation (ENSO) on a more global scale have been explored over the tropical oceans [3] as well as over land [2, 10, 30]. In addition to the effect

of natural cycles on short-duration extremes, different regions in the tropics experience anomalously wet or dry years during El Niño and La Niña events [12, 42, 43].

Thus, short-duration regional rainfall extremes as well as very high and low annual accumulation are plausibly influenced by both warming and natural cycles. In the present work, we focus on the footprint of ENSO on annual accumulation and its extremes in the tropics. In Section 2, we compare extremes in global accumulation during the ongoing pause in global warming and the preceding warming era. Apart from the fact that the average temperature during the recent period since 1998 is higher than the preceding warming era, the warming-vs-pause contrast is also a comparison between long predominantly warm and cold phases of ENSO, respectively. Keeping this in mind, in Section 3, we attempt to delineate possible connections between these changes in very low and high annual rainfall and ENSO phase transitions. We also discuss, in Section 4, the consistency between our global viewpoint using annual rainfall as a measure, and the noted trends in short-duration regional extremes. Finally, the paper concludes with a summary of results and a brief discussion in Section 5.

## II. WARMING VS PAUSE

Observations suggest that, despite the continual build-up of greenhouse gases in the atmosphere, the rate of surface warming since 1998 has been slower than in the preceding decades [9, 14]; a phenomenon referred to as the “pause” or “hiatus” in global warming. While the cause behind the ongoing hiatus has received much attention,

with many competing theories in the fray, the answer remains elusive [see, for example, the succinct summary in 22]. Rather than worry about its cause, here we view the pause — the first of its kind with possibly others to follow [34] — as a natural laboratory wherein the climate continues to evolve with one its primary variables being held relatively constant. Given this unique state of affairs, the first question we ask concerns the fate of tropical rain during the pause as compared to the immediately preceding warming era [beginning in the late 1970s, 49].

With regard to rainfall measurements, the Global Precipitation Climatology Product (GPCP) provides data at a spatial and temporal resolution of 2.5 degrees and 1 month, respectively [1]. This data is available from 1979 to the present day, thus covering the hiatus and the preceding warming era. Due to its monthly temporal and coarse spatial resolution, short-duration localized intense precipitation events which are usually the focus of studies on extremes lie outside the scope of this data. Rather, the measure which we focus on in this work, which is arguably a better yardstick for assessing the “wet-wetter, dry-drier” paradigm, is annual accumulation at every grid point. Thus, in the remainder of this manuscript, extremes refer to very high and low annual accumulation.

We begin by examining the differences in annual tropical (35S-35N) rainfall accumulation as recorded in the hiatus (1998 to 2013) and the preceding warming era (1979 to 1997). Figure 1a shows the normalised frequency distributions of annual rainfall during these two periods. These distributions are based on the union of the data from every year of the respective era, i.e., a sample size of 19 (16)  $\times$  28  $\times$  72. While frequency distributions are used for illustrating changes, cumulative distribution functions (CDF) are used for significance testing. Specifically, the Kolmogorov-Smirnov (KS) test [39] shows that the CDFs of accumulation have changed significantly between the two eras (a KS distance of 0.02, leading to a  $p$ -value close to zero, based on the null hypothesis  $H_0$ :  $\text{CDF}_{\text{hiatus}} = \text{CDF}_{\text{warming}}$ ). The changes in the tails of the distributions are better captured in Figure 1b, which shows their difference (hiatus - warming). In particular, we note that, in the global tropics, the probabilities of encountering very low (< 200 mm) and very high (> 3000 mm) accumulation have increased significantly during the hiatus. It is worth reiterating that in this comparison we are considering all the years that make up an era to be a single set, thus the increased probability of extremes in accumulation is true of the hiatus as a whole and individual years can deviate from this expectation.

In addition to the pause being warmer (on average) than the preceding warming era, the periods considered are also characterized by a transition from a relatively warm to cold phase of the ENSO [49]. This transition is evident when we examine the difference in rainfall climatology between the two eras (shown in Figure 2a). For

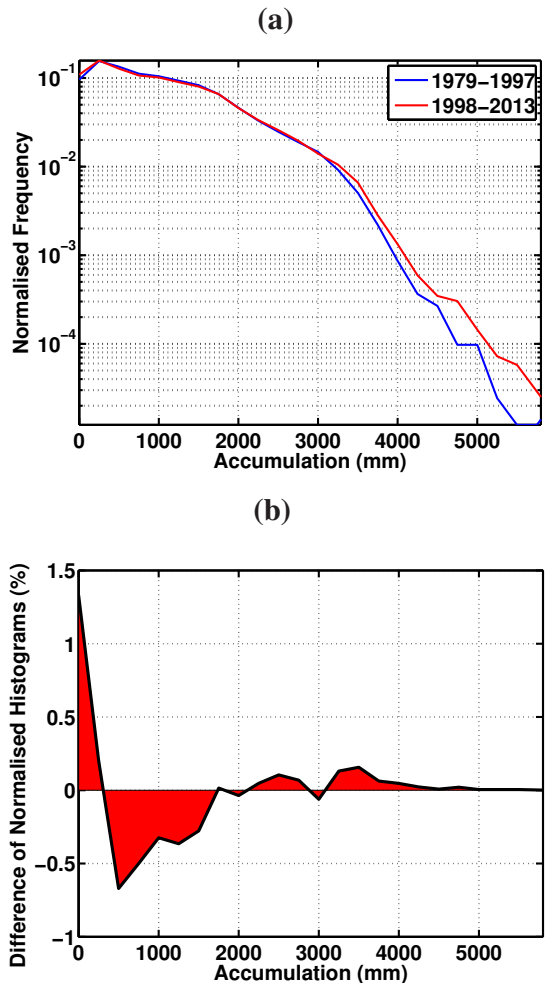


FIG. 1: (a) Normalised frequency histograms of the annual accumulation (mm) during 1979-1997 (blue) and 1998-2013 (red); and (b) Differences of these histograms. The frequencies shown are based on the union of the data from each of the two eras, i.e., sample sizes of 19 (16 years)  $\times$  28 (35S-35N)  $\times$  144 (0-360 longitude). The annual accumulation is based on 2.5-degree, monthly GPCP rainfall.

example, we see an east-west anomaly along the equatorial Pacific ocean, indicating a preference of moist convection more to the west (east) during the hiatus (warming). Similarly, the subtropical signature of the two phases can be seen with the southeastern spreading of anomalies into the southern Pacific Ocean [see, for example, 12, 42, 43, 52].

Thus, as both warming and a phase transition in ENSO are in play for the present comparison, it is not possible to attribute the noted increase in extremes of tropical accumulation to any one of these factors [see also the discussion in 40, for possible models of changes in rainfall distribution due to ENSO and warming]. To focus on the role of phase changes in ENSO on extreme accumulation, we note that the era preceding the late seventies, i.e., 1960 to the mid-1970s, was also a long

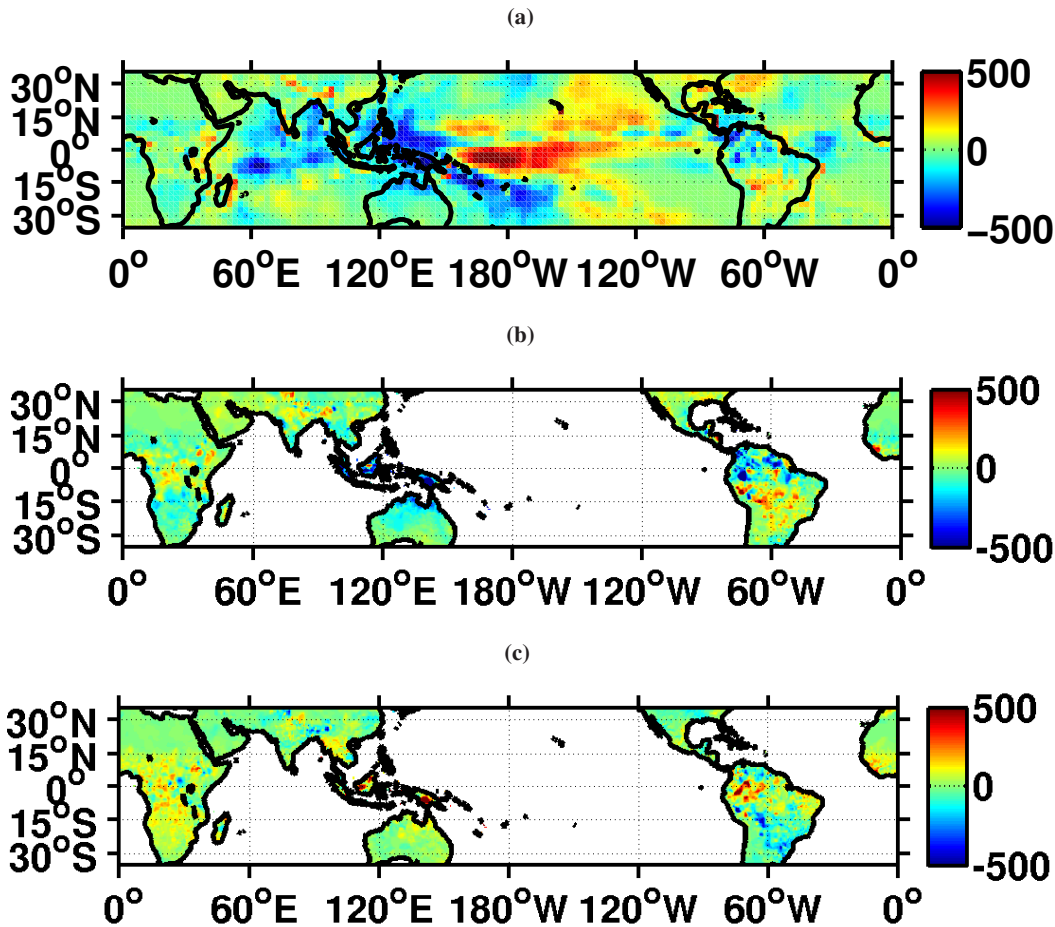


FIG. 2: (a) Spatial distribution of the difference of climatologies of annual accumulation (Warming - Pause; in mm), based on monthly, 2.5-degree, GPCP rainfall. (b) Same as (a), but over land using 0.5-degree, GPCC rainfall. (c) Same as (b), but between 1960-1978 and 1979-1997 (former - latter period).

cold phase of ENSO [see for example the discussion in 56]. In fact, both these transitions are also captured by the Pacific Decadal Oscillation index (see, for example, <http://jisao.washington.edu/pdo>). It should be kept in mind that a period identified as a particular phase of ENSO is interrupted by events of opposite polarity. For example, even though the pause is by and large a cold phase of ENSO, an examination of the PDO index reveals that the hiatus too can be partitioned into pre- and post-2005, where the latter period is dominated by La Niña conditions.

Given that there are no long-term tropical rainfall observations which cover both land and ocean, we utilise Global Precipitation Climatology Centre (GPCC) data [44], that is based on station observations (only land) and is available from 1950 onwards, at a spatial and temporal resolution of 0.5° degree and 1 month, respectively. A difference in climatologies of annual accumulation for the two phase transitions of ENSO, namely, (i) {1979-to-1997} *vs* {1998-to-2013} (warm-to-cold) and (ii) {1960-to-1978} *vs* {1979-to-1997} (cold-to-warm) are shown in Figure 2b and c, respectively. Not only are changes over

land consistent between Figures 2a and b, they are also opposite in character to those shown in Figure 2c.

Having noted the expected changes in climatologies, the specific question we seek to answer is whether a cold-to-warm transition is characterised by a decrease in extremes; i.e., is there a natural modulation of very high and low accumulation associated with ENSO phase transitions? In other words, given that the mean temperature during 1979-1997 was higher than the preceding era (1960s to the mid-1970s), if there is indeed a decrease in global extremes of accumulation, it clearly points to the role of ENSO phase transitions.

### III. EXTREMES AND ENSO TRANSITIONS

Figure 3 shows the differences between the normalised histograms of accumulation, based on GPCC data, for two phase transitions of ENSO: (i) {1979-to-1997} - {1960-to-1978} and (ii) {1998-to-2013} - {1979-to-1997}. We note that the changes in very high and low

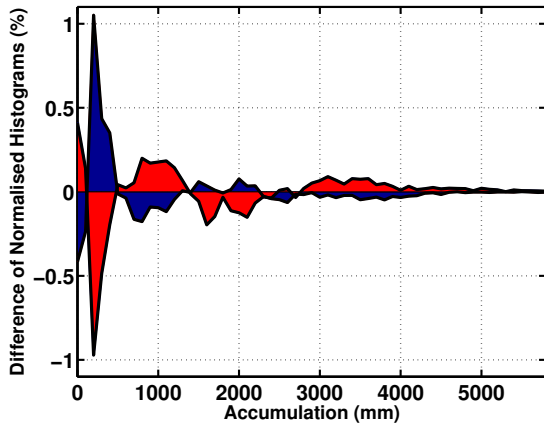


FIG. 3: Differences in the normalised histograms of the annual accumulation over land for two ENSO phase transitions,  $\{1979\text{-to-}1997\} - \{1960\text{-to-}1978\}$  (blue fill; cold to warm) and  $\{1998\text{-to-}2013\} - \{1979\text{-to-}1997\}$  (red fill; warm to cold). The estimates are based on GPCC 0.5-degree, monthly observations over land.

accumulation for the warm-to-cold transition from both GPCP (Figure 1b) and GPCC (red fill in Figure 3) are qualitatively similar. Further, even though land and ocean rainfall estimates from GPCP have different biases, the consistency with GPCC is reassuring. It is worth noting that the percentage changes in Figure 3 are smaller than in Figure 1b. This could be attributed to the higher spatial resolution of GPCC observations. More strikingly, the changes in extremes from a cold  $\{1960\text{-to-}1978\}$  to warm  $\{1979\text{-to-}1997\}$  phase of ENSO (blue fill in Figure 3) are exactly the opposite of what is observed in a warm-to-cold transition. This shows that relative changes in extremes of tropical accumulation are closely linked to ENSO.

To ascertain if there is a spatial character associated with the statistical changes described above, we utilize the crossings at approximately 200 mm and 3000 mm in Figures 1 and 3 as thresholds for very low (“dry”) and high (“wet”) accumulation, respectively. Further, the two eras that straddle a particular transition are denoted by E1 and E2 (where E2 follows E1 in time). Using this terminology, we construct “Index maps” that consist of a union of three sets. Specifically, these maps consist of geographical locations that accumulated more (less) than 3000 mm (200 mm) of rain in (i) one or more of the years of E1 and E2 (cyan); (ii) one or more of the years of E2 and none of E1 (blue); (iii) one or more of the years of E1 and none of the years in E2 (red). Thus, locations in blue (red) represent appearance (disappearance) of wet and dry regions in E2 when compared to E1.

Consider first, the warm-to-cold transition, i.e.,  $E1=\{1979\text{-to-}1997\}$  and  $E2=\{1998\text{-to-}2013\}$ , which is captured by both GPCP and GPCC data. As seen from the global GPCP product (Figure 4), new high accumulation regions appear near the western maritime continent, over the Indian Ocean and the western part of equatorial

South America (blue in Figure 4a). This is accompanied by a depletion in the eastern core of the Pacific convergence zone (red). Overall, the “new” locations still lie within climatologically rainy zones, thus indicating a rearrangement of wet regions. The aforementioned changes over land are also seen from GPCC (blue in Figures 5a,b). At the other end, the new dry points take the form of spatially coherent fringes and indicate a systematic expansion of the existing dry regions off the western coasts of Australia, and North and South America (blue in Figure 4b). As this warm-to-cold transition also involves comparison with on-an-average warmer temperatures (during the pause), it is worth noting that the expansion of dry zones is sometimes linked to global warming [33][57]. Furthermore, on land (most clearly seen in Figure 5c from GPCC due to its higher spatial resolution), we observe a mixed signal over the Australian continent (red and blue), signs of new dry zones in the western United States and northern Pakistan (blue), along with the disappearance of existing dry regions in southern Africa and a coherent shrinking of the deserts in the Sahel region of northern Africa (red). It is worth noting that these changes over land are in very good agreement with regional reports; specifically, the projected drying of the western United States [2000 onwards; see 45], the occurrence of repeated severe droughts over northern Pakistan in the early 2000s[58], and the reduction of dryness over southern Africa [1998 onwards; see Figure 2 in 16] as well as the Sahel [38].

In the cold-to-warm transition (i.e.,  $E1=\{1960\text{-to-}1978\}$  and  $E2=\{1979\text{-to-}1997\}$ ), which is only captured by GPCC data, the geographical changes (over land) seen in Figure 6 are almost exactly opposite in character to those in Figure 5. These changes are consistent with the reversal seen in the two ends of the probability distributions in Figure 3. In particular, the maritime continent shows a disappearance of wet points to the west (red), as does the western portion of equatorial South America (red). The same observation holds true for the very dry zones; here, new dry points are seen in southern Africa and the Sahel region (blue), while dryness reduces over Pakistan, western United States and much of continental Australia (red).

Thus, the answer to the question posed earlier (at the end of Section 2) is that, there appears to be an intrinsic waxing and waning, of very high and low tropical rainfall associated with ENSO phase transitions. Not only are the changes statistically significant, they also bear a coherent spatial signature.

#### IV. CONSISTENCY WITH TRENDS IN REGIONAL SHORT-DURATION EXTREMES

Having taken a global point of view, with a focus on annual accumulation, we now assess whether the changes seen above agree with previously reported trends in re-

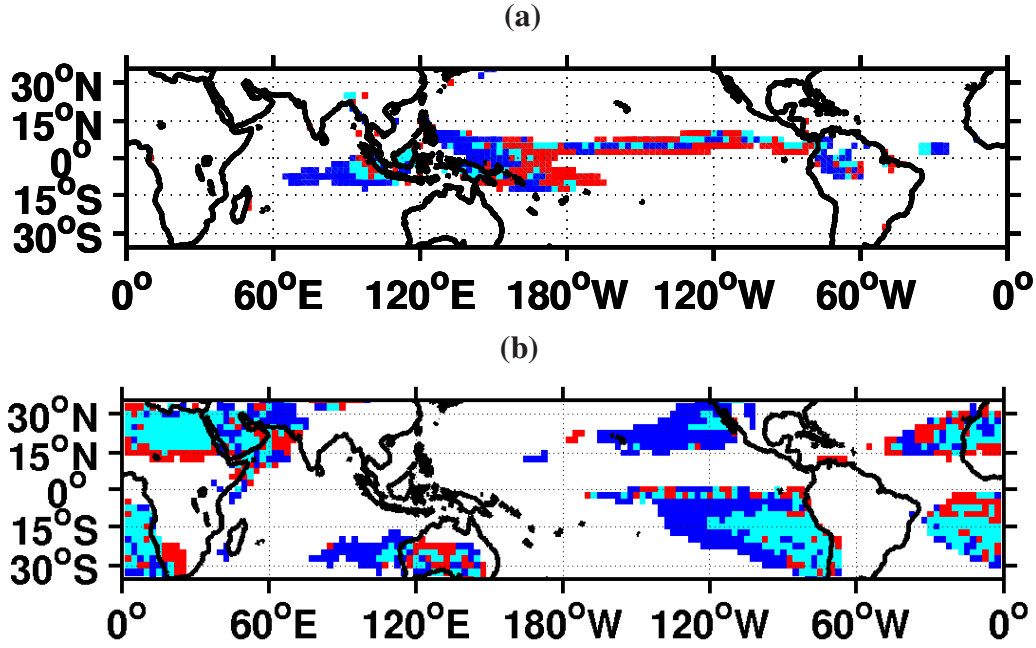


FIG. 4: Spatial distribution of the changes in the climatological (a) wet and (b) dry regions in the tropics, based on GPCP 2.5-degree, monthly observations. The colours shown represent those geographical locations that accumulated more (less) than 3000 mm (200 mm) of rain (i) in one or more of the years of {1998-to-2013} and none of {1979-to-1997} (blue); (ii) in one or more of the years of {1979-to-1997} and none of the years in {1998-to-2013} (red); and (iii) in one or more of the years of both eras (cyan).

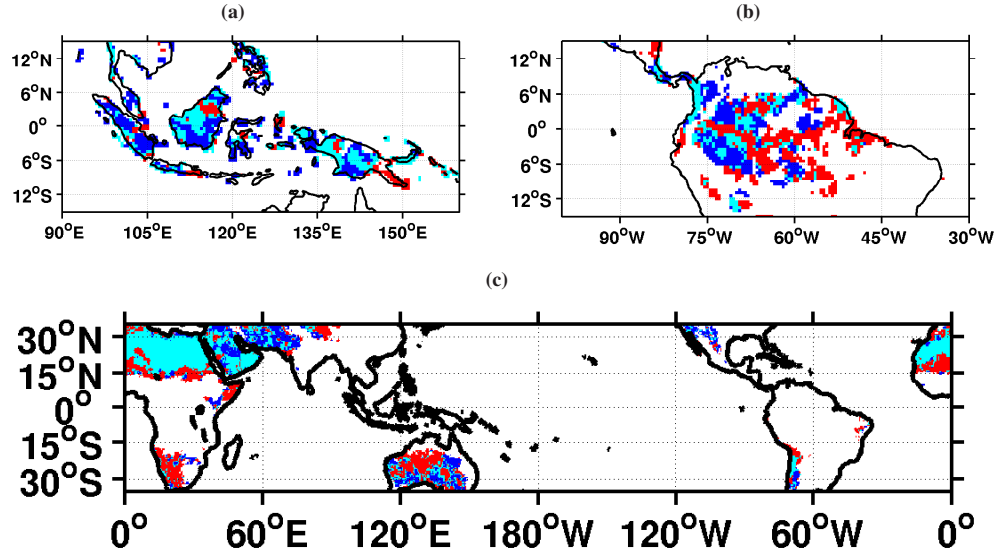


FIG. 5: Construction and color scheme same as Figure 4, but based on GPCC 0.5-degree, monthly land-only observations for the eras {1979-to-1997} and {1998-to-2013}. (a, b) Wet regions; (c) Dry regions. As before, blue/red represents appearance/disappearance of new wet/dry locations, and cyan represents no change.

gional extremes. Beginning with [24], there have been numerous reports of increasing trends in short-duration extreme rainfall events across the globe [see, for example, 13, 18, 21]. In order to show that this increase is in fact consistent with our global accumulation picture (waxing and waning), we use North America (15N-45N;

60W-130W) as an example. The motivation behind this choice stems from the fact that the region considered is large enough, so as to smooth out large local fluctuations, and thus more amenable to study extremes [see, for example, 21, and the references therein].

Following the same procedure as before, we construct



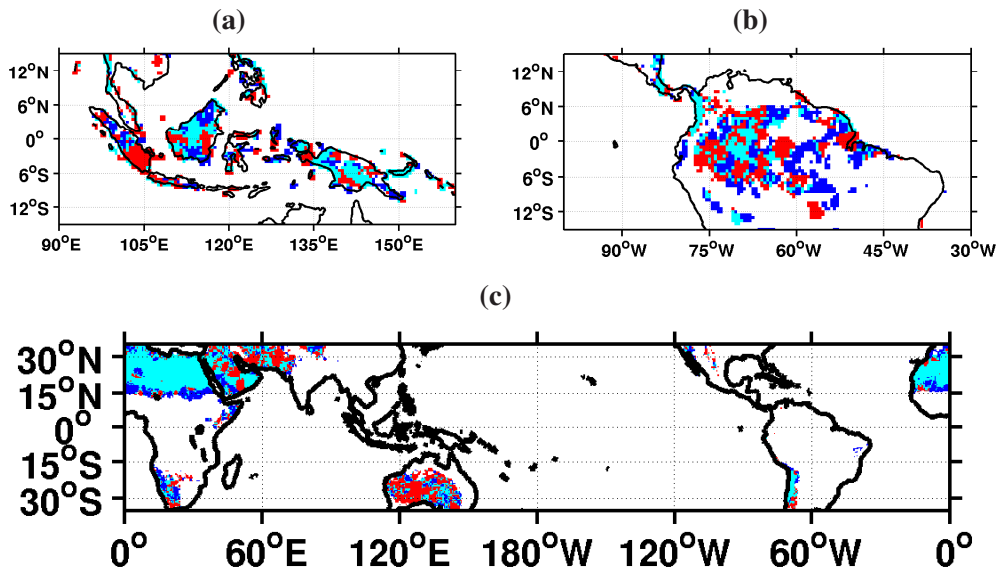


FIG. 6: Same as Figure 5, but for the eras {1960-to-1978} and {1979-to-1997}. (a, b) Wet regions; (c) Dry regions. As before, blue/red represents appearance/disappearance of new wet/dry locations, and cyan represents no change.

histograms and index maps for the two phase transitions over this region. The difference seen in the right tails of the histograms during the cold-to-warm transition (blue fill in Figure 7a) indicates an increased likelihood of exceeding annual rainfall of  $\sim 1200$  mm. Indeed, this increase is marked by an appearance of new wet spots of high accumulation (blue in Figure 7b) in {1979-to-1997} as compared to {1960-to-1978} over central US. This matches precisely with the significant short-duration extreme event trends from the mid 1970s to the late 1990s, over the contiguous central US, reported by [21]. Furthermore, as in the case of global tropics, the statistical and geographic changes associated with a warm-to-cold transition (Figure 7c) are opposite in nature to those during a cold-to-warm transition.

At first glance, in the cold-to-warm transition, the increase (decrease) in likelihood of encountering very high (low) annual rainfall over North America might appear to be contrary to the global tropical perspective presented earlier (i.e., waning of both wet and dry accumulation extremes; blue fill in Figure 3). A closer examination, however, indicates that this is not the case. In fact, the very high accumulation in the North American region forms a subset of the middle portion of the global histogram, and the changes between  $\sim 1200$  mm and  $\sim 2000$  mm in Figures 7a and 3 are similar.

## V. DISCUSSION

An immediate implication of our finding is that a warming signal can be enhanced or subdued depending on the phase of ENSO. However, disentangling their respective contributions to changes in rainfall extremes re-

mains a challenge [e.g., 11]. That said, it is worth asking if our methodology can also shed light on the more gradual contribution of warming. To this end, a comparison of extremes in similar phases of ENSO could prove fruitful. Specifically, given the data at hand, we examined the changes in extreme accumulation in two cases: (i) between two temporally well-separated cold phases of ENSO (1960-1978 vs 1998-2013); and (ii) within the warming era that was mostly a warm phase of ENSO (1979-1987 vs 1988-1997). In both these cases, the average temperature is higher in the respective latter period. The first experiment (whose results can be deduced by summing the two curves in Figure 3) yields a marginal increase on the very wet side, and, in fact, a decrease in dry extremes, neither of which is statistically significant. The second experiment (differences in PDFs not shown) showed almost no change in extremes on either side; in fact, if anything, both very high and low accumulation showed a marginal decrease. Taken together, it is difficult to argue for a clear influence of warming on the extremes of annual accumulation; in fact, internal variability, as governed by the phases of ENSO, appears to play a much more significant role than warming.

To summarise, we studied the changes in very low and high tropical rainfall accumulation from a global point of view. The main finding is that there appears to be a fundamental natural mode of variability in tropical rainfall accumulation extremes with the changing phases of ENSO. Specifically, our analysis provides clear observational evidence that a warm-to-cold (cold-to-warm) transition of ENSO is associated with waxing (waning) of extreme accumulation, both statistically and spatially, over the global tropics. The dominant role of ENSO was made clear by comparing accumulation across two tran-

sitions; specifically, cold-to-warm (1960-1978 vs 1979-1997) and a warm-to-cold (1979-1997 to 1998-2013), both of which involved a progressive increase in average global temperatures[59]. Moreover, as illustrated over the continental US, this global modulation is consistent with previously reported trends in short-duration regional extremes.

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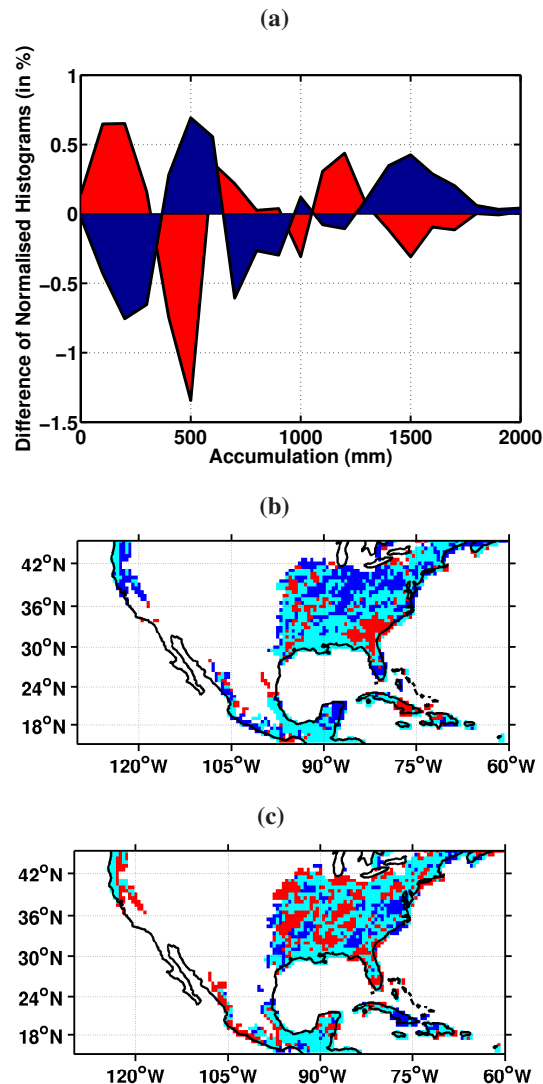


FIG. 7: (a) Same as Figure 3, but for North America (blue fill: cold-to-warm; red fill: warm-to-cold). Construction of the index map in the lower two panels is based on a threshold of 1200 mm or above, using GPCC land-only observations. The color scheme is the same as in Figure 6. (b) {1960-to-1978} and {1979-to-1997}; (c) {1979-to-1997} and {1998-to-2013}. As before, in panels (b) and (c), blue/red represents appearance/disappearance of new wet/dry locations, and cyan represents no change.

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- [57] This expansion of dry zones is part of a developing story on the widening of tropical Hadley cells, which it itself appears to have a strong ENSO component [see, for example, 35].
- [58] See for example the documentation of droughts over Pakistan, <http://pakistanweatherportal.com/2011/05/08/history-of-drought-in-pakistan-in-detail>.
- [59] In fact, recent work compares accumulation within the pause (where temperatures are fairly uniform), and once again, an increase in extremes due to a warm-to-cold transition is clearly evident [50].